On Optimal Link Activation with Interference Cancellation in Wireless Networking

Di Yuan, *Member, IEEE*, Vangelis Angelakis, *Member, IEEE*,
Lei Chen, *Student Member, IEEE*, Eleftherios Karipidis, *Member, IEEE*,
and Erik G. Larsson, *Senior Member, IEEE*

Abstract

A fundamental aspect in performance engineering of wireless networks is optimizing the set of links that can be concurrently activated to meet given signal-to-interference-and-noise ratio (SINR) thresholds. The solution of this combinatorial problem is the key element in scheduling and cross-layer resource management. Previous works on link activation assume single-user decoding receivers, that treat interference in the same way as noise. In this paper, we assume multiuser decoding receivers, which can cancel strongly interfering signals. As a result, in contrast to classical spatial reuse, links being close to each other are more likely to be active simultaneously. Our goal here is to deliver a comprehensive theoretical and numerical study on optimal link activation under this novel setup, in order to provide insight into the gains from adopting interference cancellation. We therefore consider the optimal problem setting of successive interference cancellation (SIC), as well as the simpler, yet instructive, case of parallel interference cancellation (PIC). We prove that both problems are NP-hard and develop compact integer linear programming formulations that enable us to approach the global optimum solutions. We provide an extensive numerical performance evaluation, indicating that for low to medium SINR thresholds the improvement is quite substantial, especially with SIC, whereas for high SINR thresholds the improvement diminishes and both schemes perform equally well.

D. Yuan, V. Angelakis, and L. Chen are with the Mobile Telecommunications Group, Department of Science and Technology (ITN), Linköping University, SE-601 74 Norrköping, Sweden (e-mail: diyua@itn.liu.se, vangelis.angelakis@liu.se, leich@itn.liu.se).

E. Karipidis and E. G. Larsson are with the Communication Systems Division, Department of Electrical Engineering (ISY), Linköping University, SE-581 83 Linköping, Sweden (e-mail: karipidis@isy.liu.se, erik.larsson@isy.liu.se).

I. INTRODUCTION

In wireless networking, determining the sets of links that can be active simultaneously is a cornerstone optimization task of combinatorial nature. For a link to be active, a given signal-to-interference-and-noise ratio (SINR) threshold must be met at the receiver, according to the physical connectivity model [19]. Within this domain, previous analyses assume that the communication system employs single-user decoding (SUD) receivers that treat interference as additive noise. For interference-limited scenarios, it is very unlikely that all links can be active at the same time. Hence, it is necessary to construct transmission schedules that orthogonalize link transmissions along some dimension of freedom, such as time. The schedule is composed by link subsets, each of which is a feasible solution to the link activation (LA) problem. Thus, for scheduling, repeatedly solving the LA problem becomes the dominant computational task. Intuitively, with SUD, a solution to the LA problem consists in links being spatially separated, as they generate little interference to each other. Thus, scheduling amounts to optimal spatial reuse of the time resource. For this reason, scheduling is also referred to as spatial time-division multiple access (STDMA) [28]. Optimal LA has attracted a considerable amount of attention. Problem complexity and solution approximations have been addressed in [2], [9], [18], [36]. A recent algorithmic advance is presented in [12]. Research on scheduling, which uses LA as the building block, is extensive; see, e.g, [7], [11], [29] and references therein. In addition to scheduling, LA is an integral part of more complicated resource management problems jointly addressing scheduling and other resource control aspects, such as rate adaptation and power control, as well as routing, in ad hoc and mesh networks; see, e.g., [11], [14], [26].

In the general problem setting of LA, each link is associated with a nonnegative weight, and the objective is to maximize the total weight of the active links. The weights may be used to reflect utility values of the links or queue sizes [32]. A different view of weights comes from the column generation, method proposed in [6], [7], which has become the standard solution algorithm for scheduling as well as for joint scheduling, power control, and rate adaptation [10]. The algorithm decomposes the problem to a master problem and a subproblem, both of which are much more tractable than the original. Solving the subproblem constructs a feasible LA set. In the subproblem, the links are associated with prices coming from the linear programming dual, corresponding to the weights of our LA problem. A special case of the weights is a vector of ones; in this case, the objective becomes to maximize the cardinality

of the LA set.

All aforementioned previous works on optimal LA have assumed SUD, for which interference is regarded as additive noise. In this work, we examine the problem of optimal LA under a novel setup; namely when the receivers have multiuser decoding (MUD) capability [33]. Note that, unlike noise, interference contains encoded information and hence is a structured signal. This is exploited by MUD receivers to perform interference cancellation (IC). That is, the receivers, before decoding the signal of interest, first decode the interfering signals they are able to and remove them from the received signal. For IC to take place, a receiver acts as though it is the intended receiver of the interfering signal. Therefore, an interfering signal can be cancelled, i.e., decoded at the rate it was actually transmitted, only if it is received with enough power in relation to the other transmissions, including the receiver's original signal of interest. In other words, the "interference-to-other-signals-and-noise" ratio (which is an intuitive but non-rigorous term in this context), must meet the SINR threshold of the interfering signal. With MUD, the effective SINR of the signal of interest is higher than the original SINR, with SUD, since the denominator now only contains the sum of the residual, i.e., undecoded, interference plus noise. Clearly, with MUD, concurrent activation of strongly interfering links becomes more likely, enabling activation patterns that are counter-intuitive in the conventional STDMA setting. The focus of our investigation is on the potential of IC in boosting the performance of LA. Because LA is a key element in many resource management problems, the investigation opens up new perspectives of these problems as well.

The topic of implementing MUD receivers in real systems has recently gained interest, particularly in the low SINR domain using low-complexity algorithms; see, e.g., [16]. Technically, implementing IC is not a trivial task. A fundamental assumption in MUD is that the receivers have information (codebooks and modulation schemes) of the transmissions to be cancelled. Furthermore, the transmitters need to be synchronized in time and frequency. Finally, the receivers must estimate, with sufficient accuracy, the channels between themselves and all transmitters whose signals are trying to decode. For our work, we assume that MUD is carried out without any significant performance impairments, and examine it as an enabler of going beyond the conventionally known performance limits in wireless networking. Hence, the results we provide effectively constitute upper bounds on what can be achievable, for the considered setup, in practice.

The significance of introducing MUD and more specifically IC to wireless networking is motivated by the fundamental, i.e., information-theoretic, studies of the so-called interference

channel, which accurately models the physical-layer interactions of the transmissions on coupled links. The capacity region of the interference channel is a long-standing open problem, even for the two-link case, dating back to [1], [13], [22]. Up to now, it is only known in a few special cases; see, e.g., [4], [30] for some recent contributions. Two basic findings, regarding optimal treatment of interference in the two-link case, can be summarized as follows. When the interference is very weak, it can simply be treated as additive noise. When the interference is strong enough, it may be decoded and subtracted off from the received signal, leaving an interference-free signal containing only the signal of interest plus thermal noise.

From a physical-layer perspective, the simple two-link setting above corresponds to a received signal consisting of $X = S + I + N$, where S is the signal of interest, with received power P_S and encoded with rate R_S, I is the interference signal with received power P_I encoded with rate R_I, and N is the receiver noise with power η. Assuming Gaussian signaling and capacity achieving codes, the interference I is "strong enough" to be decoded, treating the signal of interest S as additive noise, precisely if

$$\log_2\left(1 + \frac{P_I}{P_S + \eta}\right) \geq R_I \Leftrightarrow \frac{P_I}{P_S + \eta} \geq \gamma_I, \tag{1}$$

where $\gamma_I \triangleq 2^{R_I} - 1$ denotes the SINR threshold for decoding the interference signal I. If condition (1) holds, i.e., the "interference-to-other-signal-and-noise" ratio is at least γ_I, I can be decoded perfectly and subtracted off from X. Then, decoding the signal of interest S is possible, provided that the interference-free part of X has sufficient signal-to-noise ratio (SNR)

$$\log_2\left(1 + \frac{P_S}{\eta}\right) \geq R_S \Leftrightarrow \frac{P_S}{\eta} \geq \gamma_S, \tag{2}$$

where $\gamma_S \triangleq 2^{R_S} - 1$ denotes the SINR threshold for decoding signal S. By contrast, if the interference is not sufficiently strong for (1) to hold, then it must be treated as additive noise. In such a case, decoding of signal S is possible only when

$$\frac{P_S}{P_I + \eta} \geq \gamma_S. \tag{3}$$

This way of reasoning can be extended to more than one interfering signals. Towards this end, we examine the effect of IC in scenarios with potentially many links in transmission. Our study has a clear focus on performance engineering in wireless networking with arbitrary topologies. In consequence, a thorough study of the gain of IC to LA is highly motivated, in view of the pervasiveness of the LA problem in resource management of many types of

wireless networks. In the multi-link setup that we consider, the optimal scheme is to allow every receiver perform IC successively, i.e., in multiple stages. In every stage, the receiver decodes one interfering signal, removes it from the received signal, and continues as long as there exists an undecoded interfering link whose received signal is strong enough in relation to the sum of the residual interference, the signal of interest, and noise. This scheme is referred to as *successive IC (SIC)*. From an optimization standpoint, modeling SIC mathematically is very challenging, because the order in which cancellations take place is of significance. Clearly, enumerating the potential cancellation orders will not scale at all. Thus compact formulations that are able to deliver the optimal order are essential, especially under the physical connectivity model, which quantifies interference accurately.

Alternatively, a simplified IC scheme is to consider only the cancellations that can be performed concurrently, in a single stage. In this scheme, when determining the possibility for the cancellation of an interfering link, all remaining transmissions, no matter whether or not they are also being examined for cancellation, are regarded as interference. We refer to this scheme as *parallel IC (PIC)*. It is easily realized that some of the cancellations in SIC may not be possible in PIC; thus one can expect that the gain of the latter is less than that of the former. A further restriction is to allow at most one cancellation per receiver. This scheme, which we refer to as *single-link IC (SLIC)*, poses additional limit on the performance gain. However, it is the simplest scheme for practical implementation and frequently captures most of the performance gain due to IC. In comparison to SIC, PIC and SLIC are much easier to formulate mathematically, as ordering is not relevant.

In [24], we evaluated the potential of SLIC in the related problem of SINR balancing. That is, we considered as input the number of active links, let the transmit powers be variables and looked for the maximum SINR level that can be guaranteed to all links. In [3], we exploited link rate adaptation to maximize the benefits of IC to aggregate system throughput. In parallel, another set of authors has made a relevant contribution in the context of IC [27]. They considered a SIC-enabled system and introduced a greedy algorithm to construct schedules of bounded length in ad-hoc networks with MUD capabilities. There though, the interference is modeled using the protocol-based model of conflict graphs [23], which simplifies the impact of interference, in comparison to the more accurate physical connectivity model that we are using.

The overall aim of our work is to deliver a comprehensive theoretical and numerical study on optimal link activation under this novel setup in order to provide insight into the gains

from adopting interference cancellation. This is achieved through the following contributions:

- First, we introduce and formalize the optimization problems of LA in wireless networks with PIC and SIC, focusing on the latter most challenging case.
- Second, we prove that these optimization problems are NP-hard.
- Third, we develop ILP formulations that enable us to approach the global optimum for problem sizes of practical interest and thus provide an effective benchmark for the potential of IC on LA.
- Fourth, we present an extensive numerical performance evaluation that introduces insight into the maximum attainable gains of adopting IC.

We show that for some of the test scenarios the improvement is substantial. The results indicate that strong interference can indeed be taken as a great advantage in designing new notions for scheduling and cross-layer resource allocation in wireless networking with MUD capabilities.

The remainder of the paper is organized as follows. In Section II, we introduce the notation and formalize the novel optimization problems. In Section III, we prove the theoretical complexity results. In Section IV, we propose a compact ILP formulation for the LA problem with PIC having quadratic size to the number of links. For the most challenging problem of LA with SIC, we devote two sections. In Section V, we treat SIC under a common SINR threshold. By exploiting the problem structure, we show that the order of cancellations can be conveniently modeled and derive an ILP formulation of quadratic size. Then, in Section VI, we consider individual SINR thresolds. For this case, we give an ILP formulation of cubic size. In Section VII, we present and discuss simulation results evaluating the performance of all proposed IC schemes. In Section VIII, we give conclusions and outline perspectives.

II. Definition of Link Activation with Interference Cancellation

Consider a wireless system of K pairs of transmitters and receivers, forming K directed links. The discussions in the forthcoming sections can be easily generalized to a network where the nodes can act as both transmitters or receivers. Let $\mathcal{K} \triangleq \{1, \ldots, K\}$ denote the set of links. The gain of the channel between the transmitter of link m and the receiver of link k is denoted by G_{mk}, for any two $m, k \in \mathcal{K}$. The noise power is denoted by η and, for simplicity, is assumed equal at all receivers. The SINR threshold of link k is denoted by γ_k. Each link k is associated with a predefined positive activation weight w_k, reflecting its utility value or queue size or dual price. If a link is activated, its transmit power is given

and denoted by p_k, for $k \in \mathcal{K}$. A LA set is said to be feasible if the SINR thresholds of the links in the set are met under simultaneous transmission. All versions of the LA problems we consider have the same input that we formalize below.

Input: A link set $\mathcal{K}$ with the following parameters: transmit powers p_k, SINR thresholds γ_k, and link weights w_k, $\forall k \in \mathcal{K}$, and gain values G_{mk}, $\forall m, k \in \mathcal{K}$.

Consider first the LA problem with the conventional assumption of SUD, where the interference is treated as additive noise. This is the baseline version of the LA problem in our comparisons; its output is formulated as follows.

Problem LA-SUD: *Optimal link activation with single-user decoding.*

Output: An activation set $\mathcal{A} \subseteq \mathcal{K}$, maximizing $\sum\limits_{k \in \mathcal{A}} w_k$ and satisfying the conditions:

$$\frac{p_k G_{kk}}{\sum\limits_{m \in \mathcal{A} \setminus \{k\}} p_m G_{mk} + \eta} \geq \gamma_k \qquad \forall k \in \mathcal{A}. \tag{4}$$

This classical version of the LA problem can be represented by means of an ILP formulation; see, e.g., [7], [12]. A set of binary variables $x_k, \forall k \in \mathcal{K}$, is used to indicate whether or not each of the links is active. The activation set is hence $\mathcal{A} = \{k \in \mathcal{K} : \ x_k = 1\}$. In order to ease comparisons to the formulations that are introduced later, we reproduce below the formulation of LA-SUD:

$$\max \quad \sum_{k \in \mathcal{K}} w_k x_k \tag{5a}$$

$$\text{s. t.} \quad \frac{p_k G_{kk} + M_k(1 - x_k)}{\sum\limits_{m \neq k} p_m G_{mk} x_m + \eta} \geq \gamma_k \qquad \forall k \in \mathcal{K}, \tag{5b}$$

$$x_k \in \{0, 1\} \qquad \forall k \in \mathcal{K}. \tag{5c}$$

The objective function (5a) aims to maximize the total weight of the LA set. The constraints (5b) formulate the SINR criteria. If $x_k = 1$, indicating that link k is active, the kth inequality constrains the SINR of link k to be at least γ_k. For the case that link k is not active, $x_k = 0$, the kth inequality in (5b) is always satisfied, i.e., it has null effect, if parameter M_k is set to a sufficiently large value. By construction, an obvious choice is $M_k = \sum\limits_{m \neq k} p_m G_{mk} \gamma_k + \eta \gamma_k - p_k G_{kk}$. Note that the size of the formulation (5), both in the numbers of variables and constraints, is of $O(K)$.

Now, consider the same system but with receivers having MUD capability that enable cancellation of strongly interfering links. We distinguish between IC in a single stage (PIC)

and in multiple stages (SIC). In the former, to cancel the transmission of an interfering link, all other signals of active links, including the signal of interest, are considered to be additive noise, independent of other cancellation decisions at the same receiver. A formal definition of the output is given below.

Problem LA-PIC: *Optimal link activation with parallel interference cancellation.*
Output: An activation set $\mathcal{A} \subseteq \mathcal{K}$ and the set $\mathcal{C}_k \subseteq \mathcal{A} \setminus \{k\}$ of cancelled transmissions for each $k \in \mathcal{A}$, maximizing $\sum\limits_{k \in \mathcal{A}} w_k$ and satisfying the conditions:

$$\frac{p_m G_{mk}}{\sum\limits_{n \in \mathcal{A} \setminus \{m\}} p_n G_{nk} + \eta} \geq \gamma_m \qquad \forall m \in \mathcal{C}_k,\ \forall k \in \mathcal{A}, \tag{6a}$$

$$\frac{p_k G_{kk}}{\sum\limits_{m \in \mathcal{A} \setminus \{k, \mathcal{C}_k\}} p_m G_{mk} + \eta} \geq \gamma_k \qquad \forall k \in \mathcal{A}. \tag{6b}$$

The set of conditions (6a) ensures that the specified cancellations can take place. For the receiver of link k to cancel the transmission of link m, the receiver of k acts as if it was the receiver of m. Hence, the "interference-to-other-signals-and-noise" ratio incorporates in the numerator the received power $p_m G_{mk}$ of the interfering link m and in the denominator the received power $p_k G_{kk}$ of own link k. This ratio must satisfy the SINR threshold of the signal m to be decoded. The set of conditions (6b) formulates the SINR requirements for the signals of interest, taking into account the effect of IC in the SINR ratio. That is, the cancelled terms are removed from the sum in the denominator, determining the aggregate power of the undecoded interference which is treated as additive noise.

For SIC, the output must be augmented in order to specify, in addition to the cancellations $\mathcal{C}_k$, by the receiver of $k \in \mathcal{A}$, the order in which they take place. A formal definition of the output is given below.

Problem LA-SIC: *Optimal link activation with successive interference cancellation.*
Output: An activation set $\mathcal{A} \subseteq \mathcal{K}$ and the set $\mathcal{C}_k \subseteq \mathcal{A} \setminus \{k\}$ of cancelled transmissions along with a bijection $b_k : \mathcal{C}_k \mapsto \{1, \ldots, |\mathcal{C}_k|\}$ for each $k \in \mathcal{A}$, maximizing $\sum\limits_{k \in \mathcal{A}} w_k$ and satisfying the conditions:

$$\frac{p_m G_{mk}}{\sum\limits_{n \in \mathcal{A} \setminus \{m, q \in \mathcal{C}_k:\ b_k(q) < b_k(m)\}} p_n G_{nk} + \eta} \geq \gamma_m \qquad \forall m \in \mathcal{C}_k,\ \forall k \in \mathcal{A}, \tag{7a}$$

$$\frac{p_k G_{kk}}{\sum\limits_{m \in \mathcal{A} \setminus \{k, \mathcal{C}_k\}} p_m G_{mk} + \eta} \geq \gamma_k \qquad \forall k \in \mathcal{A}. \tag{7b}$$

Similarly to LA-PIC, the set of conditions (7a) formulates the requirement for SIC and the set (7b) the requirement for decoding the signals of interest, taking into account the effect of IC in the SINR ratio. In the output, the cancellation sequence for each k in the activation set is given by the bijection b_k; the bijection defines a unique mapping of the link indices in the cancellation set $\mathcal{C}_k$ to the IC order numbers in the cancellation sequence. That is, $b_k(m), m \in \mathcal{C}_k$ defines the stage at which link m is cancelled by the receiver of link k. The bijection is used in the IC conditions (7a), in order to exclude from the sum in the denominator, the interference terms that have been cancelled in stages prior to m.

III. Complexity

The baseline problem, LA-SUD, is known to be NP-hard; see, e.g., [18]. For a combinatorial optimization problem, introducing new elements to the problem structure may change the complexity level, potentially making the problem easier to solve. Hence, without additional investigation, the NP-hardness of LA-SUD does not carry over to LA with IC. In this section, we provide the theoretical result that problems LA-PIC and LA-SIC remain NP-hard, using a unified proof applicable to both cases.

Theorem 1: Problem LA-PIC is NP-hard.

Proof: We provide a reduction from LA-SUD to LA-PIC. Considering an arbitrary instance of LA-SUD, we construct an instance of LA-PIC as follows. For each link $k \in \mathcal{K}$, we go through all other links in $\mathcal{K} \setminus \{k\}$ one by one. Let m be the link under consideration. The power of link k is set to

$$p'_k \triangleq \max \left\{ p_k, \left(\frac{p_m G_{mk}}{\gamma_m - \varepsilon} - \eta \right) / G_{kk} \right\}, \tag{8}$$

where ε is a small positive constant. By (8), the power of k is either kept as before, or grows by an amount such that $\frac{p_m G_{mk}}{p'_k G_{kk} + \eta} < \gamma_m$. Therefore, link k is not able to decode the signal of m, i.e., the IC condition of LA-PIC cannot be satisfied, even in the most favorable scenario that all other links, apart from m and k, are inactive.

After any power increase of link k, we make sure that this update does not have any effect in the application of (8) to the other links. This is achieved by scaling down the channel gain G_{km} as

$$G'_{km} \triangleq G_{km} p_k / p'_k, \tag{9}$$

meaning that for any m, the received signal strength from k remains the same as in the original instance of LA-SUD. As a result, even though IC is allowed in the instance of LA-

PIC, no cancellation will actually take place, since none of the IC conditions holds due to the scalings in (8) and (9).

By the construction above, for each link $k \in \mathcal{K}$ the total interference that is treated as noise in the instance of LA-PIC equals that in the instance of LA-SUD. Thus, the denominator of the SINR of the signal of interest does not change. On the other hand, the numerator may have grown from p_k to p'_k. To account for this growth, the SINR threshold γ_k is set to

$$\gamma'_k \triangleq \gamma_k p_k / p'_k. \tag{10}$$

In effect, the increase of the power on a link, if any, is compensated for by the new SINR threshold. Note that, because $p'_k/p_k \geq 1$, γ'_k prohibits cancellation of the kth signal by any receiver other than the kth one.

From the construction, one can conclude that a LA set is feasible in the instances of LA-SUD, if and only if this is the case in the instance of LA-PIC. In addition, the reduction is clearly polynomial. Hence the conclusion. ∎

Corollary 1: Problem LA-SIC is NP-hard.

Proof: The result follows immediately from the fact that, in the proof of Theorem 1, the construction does not impose any restriction on the number of links to be cancelled, nor to the order in which the cancellations take place. ∎

IV. Link Activation with Parallel Interference Cancellation

In this section, we propose a compact ILP formulation for LA-PIC. In addition to the $x_k,\ \forall k \in \mathcal{K}$, variables in (5), we introduce a second set of binary variables, $y_{mk},\ \forall m, k \in \mathcal{K},\ m \neq k$. Variable y_{mk} is one if the receiver of link k decodes and cancels the interference from link m and zero otherwise. The output of LA-PIC is then defined by $\mathcal{A} = \{k \in \mathcal{K} : x_k = 1\}$ and $\mathcal{C}_k = \{m \in \mathcal{A} \setminus \{k\} :\ y_{mk} = 1\}$, for each $k \in \mathcal{A}$. The proposed formulation for LA-PIC is

$$\max \quad \sum_{k \in \mathcal{K}} w_k x_k \tag{11a}$$

$$\text{s. t.} \quad y_{mk} \leq x_m \qquad \forall m, k \in \mathcal{K},\ m \neq k, \tag{11b}$$

$$y_{mk} \leq x_k \qquad \forall m, k \in \mathcal{K},\ m \neq k, \tag{11c}$$

$$\frac{p_k G_{kk} + M_k(1 - x_k)}{\sum\limits_{m \neq k} p_m G_{mk}(x_m - y_{mk}) + \eta} \geq \gamma_k \qquad \forall k \in \mathcal{K}, \tag{11d}$$

$$\frac{p_m G_{mk} + M_{mk}(1 - y_{mk})}{\sum\limits_{n \neq m} p_n G_{nk} x_n + \eta} \geq \gamma_m \qquad \forall m, k \in \mathcal{K},\ m \neq k, \tag{11e}$$

$$y_{mk} \in \{0, 1\} \qquad \forall m, k \in \mathcal{K},\ m \neq k, \tag{11f}$$

$$x_k \in \{0, 1\} \qquad \forall k \in \mathcal{K}. \tag{11g}$$

The objective function (11a) is the same as (5a) for LA-SUD. The first two sets of inequalities, (11b) and (11c), pose necessary conditions on the relation between the variable values. Namely, a cancellation can take place, i.e., $y_{mk} = 1$, only if both links k and m are active, i.e., $x_k = x_m = 1$. The set of inequalities (11d) formulates the SINR requirements (6b) for decoding the signals of interest, in a way similar to (5b) for LA-SUD, with the difference that here the cancelled interference terms are subtracted from the denominator using the term $x_m - y_{mk}$. Note that, without (11b), the formulation will fail, as in (11d) it would allow to reduce the denominator of the ratio by subtracting non-existing interference from non-active links. The next set of constraints (11e) formulates the condition (6a) for PIC: y_{mk} can be set to one only if the interference from link m, $p_m G_{mk}$, is strong enough in relation to all other active signals, including the signal of interest. If the ratio meets the SINR threshold γ_m for link m, cancellation can be carried out. Setting y_{mk} to zero is always feasible, on the other hand, provided that the parameter M_{mk} is large enough. A sufficiently large value is $M_{mk} \triangleq \sum\limits_{n \neq m} p_n G_{nk} \gamma_m + \eta\gamma_m - p_m G_{mk}$. The construction of (11e) reflects the fact of performing all cancellations in a single stage, as in cancelling the signal of link m, other transmissions being cancelled in parallel are treated as additive noise. Note that the model remains in fact valid even if (11c) is removed. Doing so would allow the receiver of an inactive link to perform IC. However, since an inactive link does not contribute at all to the objective function, this is a minor "semantic" mismatch that can be simply alleviated by post-processing.

For practical purposes, each receiver may be allowed to cancel the signal of at most one interfering link. The resulting LA problem, denoted LA-SLIC, can be easily formulated by adapting the formulation (11) for LA-PIC. The only required change is the addition of the set of constraints

$$\sum_{m \neq k} y_{mk} \leq 1 \qquad \forall k \in \mathcal{K}, \tag{12}$$

that restricts each receiver to cancel at most one interfering transmission.

The size of the formulation (11), both in the numbers of variables and constraints, is of $O(K^2)$. Thus, the formulation is compact and its size grows by one magnitude in comparison to (5). In fact, to incorporate cancellation between link pairs, one cannot expect any optimization formulation of smaller size.

When implementing the formulation, two pre-processing steps can be applied to reduce the size of the problem and hence speed-up the calculation of the solution. First, the links that are infeasible, taking into account only the receiver noise, are identified by checking for every receiver whether the received SNR meets the SINR threshold for activation. If the answer is "false", i.e., $\frac{p_k G_{kk}}{\eta} < \gamma_k$, then link k is removed from consideration by fixing the x_k variable to zero. Second, the link pairs for which cancellation can never take place are found by checking, for every receiver and interfering signal, whether the "interference-to-signal-of-interest-and-noise" ratio meets the SINR threshold for decoding the interference signal. If the answer is "false", i.e., $\frac{p_m G_{mk}}{p_k G_{kk} + \eta} < \gamma_m$, then link k cannot decode the interference from m and this option is eliminated from the formulation by setting the respective variable y_{mk} to zero.

V. Link Activation with Successive Interference Cancellation Under Common SINR Threshold

Incorporating the optimal IC scheme, SIC, to the LA problem is highly desired, since it may activate sets that are infeasible by PIC. However, using ILP to formulate compactly the solution space of LA-SIC, is challenging. This is because the formulation has to deal, for each link, with a bijection giving the cancellation sequence. We propose an ILP approach and present it in two steps. In this section, we consider LA-SIC under the assumption that all links have a common SINR threshold for activation, i.e., $\gamma_k = \gamma, \ \forall k \in \mathcal{K}$. In the next section, we address the general case of individual SINR thresholds.

For SIC under common SINR threshold, we exploit the problem structure and show that the optimal cancellation order can be handled implicitly in the optimization formulation. As a result, we show that LA-SIC can in fact be formulated as compactly as LA-PIC, i.e., using $O(K^2)$ variables and constraints. The idea is to formulate an optimality condition on the ordering of IC. To this end, consider an arbitrary link k and observe that meeting the SINR threshold for decoding the signal of interest is equivalent to having in the receiver, after IC, a total amount of undecoded interference and noise at most equal to $p_k G_{kk}/\gamma$. We refer to this term as the *interference margin* u_k . Similarly, the interference margin that allows

cancellation of the interference from link m at the receiver of link k is $u_{mk} \triangleq p_m G_{mk}/\gamma$. Consider any two interfering links m and n, and suppose $u_{mk} > u_{nk}$. Note that, because the SINR threshold is common, the condition is equivalent to $p_m G_{mk} > p_n G_{nk}$, i.e., the receiver of link k experiences stronger interference from m. If the condition holds, the cancellation of m should be "easier" in some sense. Thus, one may expect that if k can decode both m and n, the decoding of m should take place first. In the following, we prove a theorem, stating that this is indeed the case at the optimum—there exists an optimal solution having the structure in which if a weaker interference signal can be cancelled, then any stronger one is cancelled before it.

Theorem 2: If $u_{mk} > u_{nk}$ and the receiver of link k is able to cancel the signal of n, then it is feasible to cancel the signal of m before n and there exists at least one optimum having this structure in the cancellation sequence.

Proof: Let I_{nk} denote the total power of undecoded interference and noise when the receiver of k decodes the signal from n. Assume that m has not been cancelled in a previous stage. Then, $p_m G_{mk}$ is part of I_{nk}. Successful cancellation of n means that $I_{nk} \leq u_{nk}$. Since $u_{nk} < u_{mk}$, it holds that $I_{nk} < u_{mk}$. Consider now decoding the signal of m immediately before n. Thus for this cancellation, the total power of the undecoded interference and noise incorporates the interference of n, but not that of m, i.e., $I_{mk} = I_{nk} + p_n G_{nk} - p_m G_{mk}$. Because $u_{mk} > u_{nk}$ implies $p_m G_{mk} > p_n G_{nk}$, it holds that $I_{mk} < I_{nk}$. Since $I_{nk} < u_{mk}$, the cancellation condition $I_{mk} \leq u_{mk}$ is satisfied. After cancelling m, IC can still take place for n, because the new I_{nk} is decreased by $p_m G_{mk}$. Consequently, both m and n can be cancelled. Obviously, doing so will not reduce the number of active links and the theorem follows. ■

By Theorem 2, for each link k, we can perform a pre-ordering of all other links in descending order of their interference margins. SIC at link k can be restricted to this order without loss of optimality. At the optimum, the cancellations performed by k, for interfering links that are active, will follow the order, until no more additional cancellations can take place. In this optimal solution, when considering the cancellation condition of interfering link m, interference can only originate from links appearing after m in the sorted sequence.

We propose an ILP formulation based on Theorem 2. The formulation uses the same variables of (11) for LA-PIC, as there is no need to formulate the cancellation order explicitly. The sorted sequence is denoted by, for each link $k \in \mathcal{K}$, a bijection $i_k : \mathcal{K} \backslash \{k\} \mapsto \{1, \ldots, K-1\}$, where $i_k(m)$ is the position of link m in the sorted sequence. The sorting results in

$i_k(m) > i_k(n)$ if $u_{mk} < u_{nk}$. In case of $u_{mk} = u_{nk}$, the tie can be broken arbitrarily without affecting the optimization result. In addition, let $c_{mk} \triangleq K - 1 - i_k(m)$ denote the number of links appearing after m in the sorted sequence for k. The proposed formulation for LA-SIC under common SINR threshold is

$$\max \quad \sum_{k\in\mathcal{K}} w_k x_k \tag{13a}$$

$$\text{s. t.} \quad y_{mk} \le x_m \qquad \forall m,k \in \mathcal{K},\ m \neq k, \tag{13b}$$

$$y_{mk} \le x_k \qquad \forall m,k \in \mathcal{K},\ m \neq k, \tag{13c}$$

$$\frac{p_k G_{kk} + M_k(1 - x_k)}{\sum\limits_{m\neq k} p_m G_{mk}(x_m - y_{mk}) + \eta} \ge \gamma \qquad \forall k \in \mathcal{K}, \tag{13d}$$

$$\frac{p_m G_{mk} + M_{mk}(1 - y_{mk})}{\sum\limits_{n\neq k,\ i_k(n)>i_k(m)} p_n G_{nk} x_n + p_k G_{kk} + \eta} \ge \gamma \qquad \forall m,k \in \mathcal{K},\ m \neq k, \tag{13e}$$

$$\sum_{n\neq k,\ i_k(n)>i_k(m)} y_{nk} \le c_{mk}(1 - x_m + y_{mk}) \qquad \forall m,k \in \mathcal{K},\ m \neq k, \tag{13f}$$

$$y_{mk} \in \{0,1\} \qquad \forall m,k \in \mathcal{K},\ m \neq k, \tag{13g}$$

$$x_k \in \{0,1\} \qquad \forall k \in \mathcal{K}. \tag{13h}$$

The first three constraint sets (13b)–(13d) have the same meaning with (11b)–(11d) for LA-PIC; see Section IV. The constraint set (13e) formulates the conditions (7a) for SIC, making use of Theorem 2. Consider the condition for cancellation of signal m from receiver k in stage $i_k(m)$. Then, in the denominator of the ratio, the sum of undecoded interference is limited to the transmissions coming after m in the sorted sequence of k, since all other active links with higher interference margin than m have already been cancelled. The formulation is however not complete without (13f). This set of constraints, in fact, ensures the optimality condition set by Theorem 2 and utilized in (13e). That is, if both m and n are active, $u_{mk} > u_{nk}$, and n is cancelled by k, then m is cancelled by k as well. Equivalently speaking, if m is active but not cancelled by k, then none of the other links after m in the sequence of k may be cancelled. Examining (13f), we see that it has no effect as long as x_m equals y_{mk}. If link m is active but not cancelled, corresponding to $x_m = 1$ and $y_{mk} = 0$, the right-hand side of (13f) becomes zero, and therefore no cancellation will occur for any n having position

after m in the ordered sequence. Also, note that the case $x_m = 0$ but $y_{mk} = 1$ cannot occur, because of (13b).

Given a solution to the formulation (13), the cancellation sequence of each active link k, i.e., the bijection b_k in the definition of LA-SIC in Section II, is easily obtained by retrieving from the predefined bijection i_k the elements with $y_{km} = 1$. The compactness of the formulation (13) is manifested by the fact that its size, in both the numbers of variables and constraints, is of $O(K^2)$. Thus, provided that there is a common SINR threshold for activation, we have formulated LA-SIC as compactly as LA-PIC.

When implementing the formulation (13), similar pre-processing steps with (11) for LA-PIC can be applied to reduce the size of the problem. First, the infeasible links are removed for consideration by fixing x_k to zero when $u_k < \eta$. Second, the infeasible IC options are eliminated from the formulation by fixing y_{mk} to zero when $u_{mk} < p_k G_{kk} + \eta$.

VI. Link Activation with Successive Interference Cancellation Under Individual SINR Thresholds

In this section, we consider the LA-SIC problem under the most general setup; namely when the links have individual SINR thresholds. Differently from the common SINR case, treated in Section V, a pre-ordering of the sequence of potential IC does not apply. The reason is that the interference margin u_{mk} does not depend anymore only on the received power $p_m G_{mk}$ but also on the link-specific SINR threshold γ_m. To see this point, consider a scenario where link k attempts to cancel the signal of two interfering links m and n in two consecutive stages. Denote by I the sum of the remaining interference, other than m or n, the received power of link k's own signal, and noise. Assume a mismatch between the relation of interference margin and that of received power: $p_m G_{mk} < p_n G_{nk}$ but $u_{mk} > u_{nk}$ because $\gamma_m < \gamma_n$. If k cancels m and then n, the cancellation conditions are $u_{mk} \geq p_n G_{nk} + I$ and $u_{nk} \geq I$. Reversing the cancellation order leads to the conditions $u_{nk} \geq p_m G_{mk} + I$ and $u_{mk} \geq I$. For our example, we let $I = 0.5$. Consider two sets of values for the other parameters. The values in the first set are: $u_{mk} = 3$, $u_{nk} = 1$, $p_m G_{mk} = 1$, $p_n G_{nk} = 2$ and in the second set are: $u_{mk} = 2$, $u_{nk} = 1$, $p_m G_{mk} = 0.5$ $p_n G_{nk} = 2$. For the first set, both interfering links can be cancelled only if cancellation applies to m first, whereas the opposite order must be used for the second set. Hence the interference margin (or received power) does not provide a pre-ordering for cancellation.

In the following, we propose an ILP formulation for LA-SIC under individual SINR

thresholds, that explicitly accounts for the cancellation order. Our approach is to introduce for each pair of links, $m, k \in \mathcal{K}$, a set of binary variables y_{mk}^t and represent the cancellation stage by the superscript t. Variable y_{mk}^t is one if and only if the receiver of link k cancels the interference from link m at stage t. The effect is that, for each link k, the solution values of y_{mk}^t order the feasible cancellations; hence, they have a direct correspondence to the output bijection b_k of LA-SIC, defined in Section II. It is apparent that the index t ranges between one and $K-1$. In practice, due to computational considerations, we may want to restrict the maximum number of cancellation stages. To this end, we define, for each $k \in \mathcal{K}$, the integer parameters $T_k \leq K-1$ and the sets $\mathcal{T}_k \triangleq \{1, \ldots, T_k\}$. The proposed formulation of the general LA-SIC problem, under individual SINR thresholds and restricted cancellation stages, is

$$\max \quad \sum_{k \in \mathcal{K}} w_k x_k \tag{14a}$$

s. t.

$$\sum_{t=1}^{T_k} y_{mk}^t \leq x_m, \qquad \forall m, k \in \mathcal{K},\ m \neq k, \tag{14b}$$

$$\sum_{m \neq k} y_{mk}^t \leq x_k, \qquad \forall k \in \mathcal{K},\ \forall t \in \mathcal{T}_k, \tag{14c}$$

$$\frac{p_k G_{kk} + M_k(1 - x_k)}{\sum\limits_{m \neq k} p_m G_{mk} \Big(x_m - \sum\limits_{t=1}^{T_k} y_{mk}^t \Big) + \eta} \geq \gamma_k \qquad \forall k \in \mathcal{K}, \tag{14d}$$

$$\frac{p_m G_{mk} + M_{mk}(1 - y_{mk}^t)}{\sum\limits_{n \neq m,k} p_n G_{nk} \Big(x_n - \sum\limits_{t'=1}^{t-1} y_{nk}^{t'} \Big) + p_k G_{kk} + \eta} \geq \gamma_m \qquad \forall m, k \in \mathcal{K},\ m \neq k,\ \forall t \in \mathcal{T}_k, \tag{14e}$$

$$\sum_{m \neq k} y_{mk}^t \leq \sum_{m \neq k} y_{mk}^{t-1} \qquad \forall k \in \mathcal{K},\ \forall t \in \mathcal{T}_k \setminus \{1\}, \tag{14f}$$

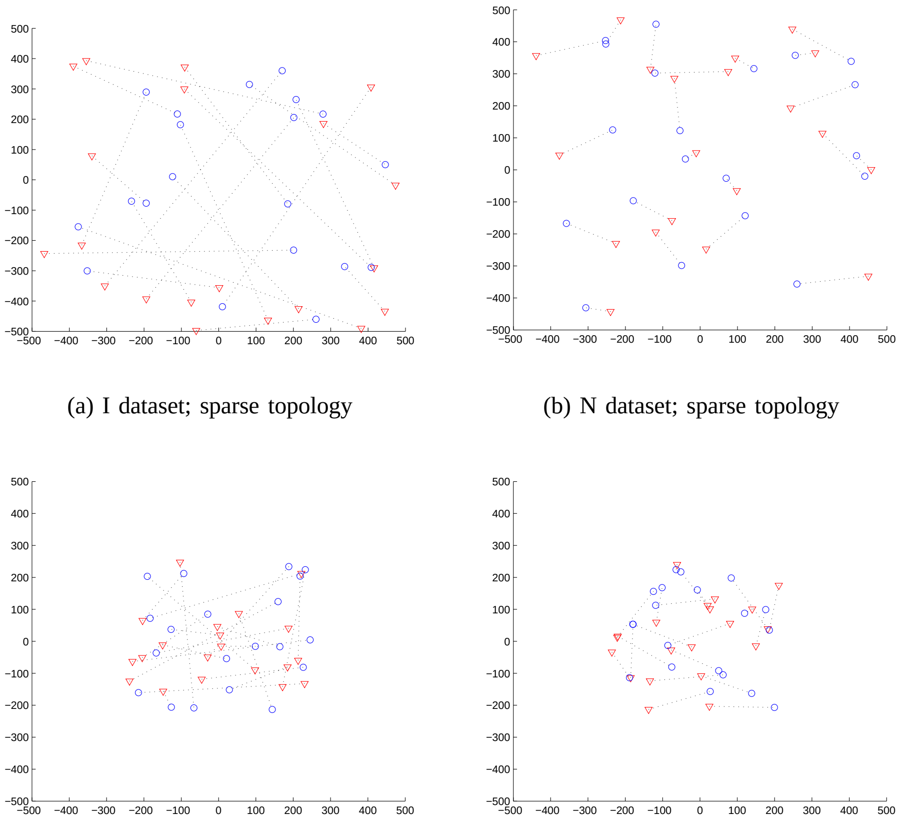
$$y_{mk}^t \in \{0, 1\} \qquad \forall m, k \in \mathcal{K},\ m \neq k,\ \forall t \in \mathcal{T}_k, \tag{14g}$$

$$x_k \in \{0, 1\} \qquad \forall k \in \mathcal{K}. \tag{14h}$$

The conditions (14b)–(14c) have similar role with (13b)–(13c). Namely, only when links k and m are active, the receiver of k can consider to cancel the transmission of m. In addition, the summation over t in (14b) ensures that link m is cancelled in at most one

stage. Furthermore, the summation over m in (14c) enforces each receiver to perform at most one cancellation per stage. This removes equivalent solutions, without compromizing optimality, to enhance computational efficiency. The SINR requirements for decoding the signals of interest are set in (14d), similarly to (13d). In the denominator, all cancelled links, regardless of the stage the cancellation is performed, are removed from the sum of undecoded interference. The next set of constraints (14e) formulates the requirement for the cancellation of link m by link k at stage t. The active interfering transmissions that have been cancelled before stage t are excluded from the sum of undecoded interference in the denominator of the ratio. The constraints (14e) are formulated with the convention that the sum within the parenthesis in the denominator of the ratio is zero for $t = 1$. Note that, even though for each receiver k and interfering link m, T_k constraints are formulated, due to (14b), all but at most one will be trivially satisfied by the respective y^t_{mk} variabls being equal to zero. The constraints (14f) are not mandatory for the correctness of the formulation, but their role is to enhance the computational efficiency. These constraints ensure that the cancellations are performed as “early” as possible, i.e., there are no “idle” stages at which no cancellation takes place and which are followed by later stages where cancellation takes place. Otherwise, if m_1 and m_2 are cancelled by k, and the cancellation of the former takes place first, the cancellations can be performed at any two stages t_1 and t_2, as long as $t_1 < t_2$. Clearly, such solutions are all equivalent to each other, and the presence of them slows down the computational process.

Since (14) formulates the most general LA-SIC problem, it also applies to the common-SINR case of Section V. Its computational efficiency though is significantly lower than the respective of formulation (13). The reason is that its size is one magnitude larger than (13), i.e., the numbers of variables and constraints grow from $O(K^2)$ to $O(K^3)$. However, we note that the formulation (14) remains compact. In order to deal with the scalability issue, one may resort to restrict the maximum number of cancellations, T_k, to a constant being considerably lower than $K-1$. Typically, doing so has little impact on the solution quality, because most of the performance gain from IC is due to the first few cancellations. Also, when implementing the formulation (14), similar pre-processing steps with (13) can be applied, see Section V, to reduce the size of the problem.



(a) I dataset; sparse topology

(b) N dataset; sparse topology

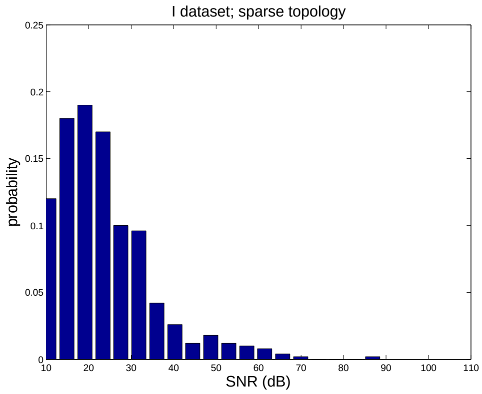
(c) I dataset; dense topology

(d) N dataset; dense topology

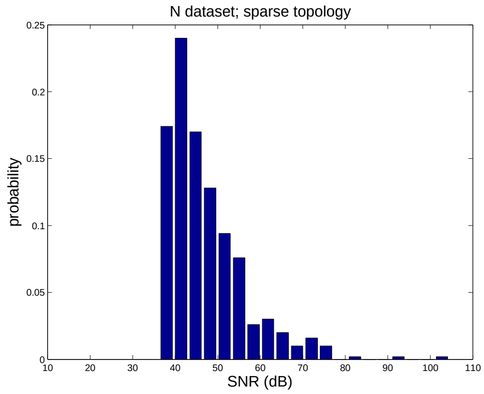
Fig. 1. Instances of a 20-link network for different datasets and densities; transmitters marked with circles, receivers with triangles.

VII. Numerical results

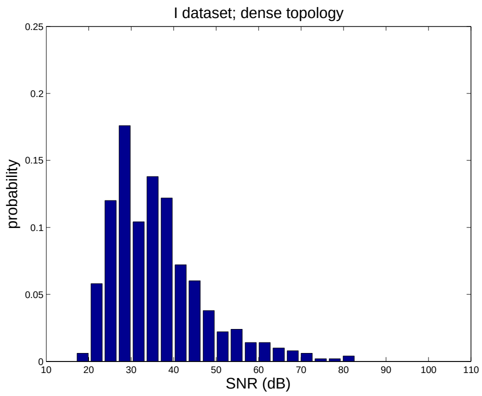
This section presents a quantitative study of the effect that IC has on the optimal LA problem in wireless networking. The ILP formulations, proposed in Sections IV–VI, are utilized to conduct extensive simulation experiments on randomly generated network instances with various topologies, densities, cardinalities, and SINR thresholds. Nodes are uniformly scattered in square areas of $1000\text{m} \times 1000\text{m}$ and $500\text{m} \times 500\text{m}$, in order to create sparse and dense topologies, respectively. Two types of datasets are generated. The first one takes an information-theoretic viewpoint and is henceforth denoted dataset I. To this end, the transmitter-receiver matchings are arbitrarily chosen [8], [20], with the sole criterion of feasible single-link activation. Thus, the links have arbitrary length within the test area, provided that their SNR is larger than the SINR threshold required for activation. The second dataset provides a rather networking-oriented approach [15], [31] and is henceforth denoted



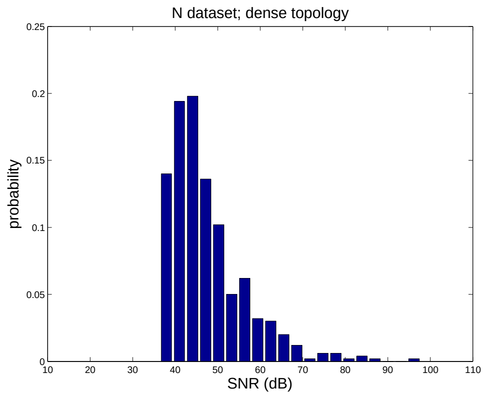
(a) I dataset; sparse topology



(b) N dataset; sparse topology



(c) I dataset; dense topology

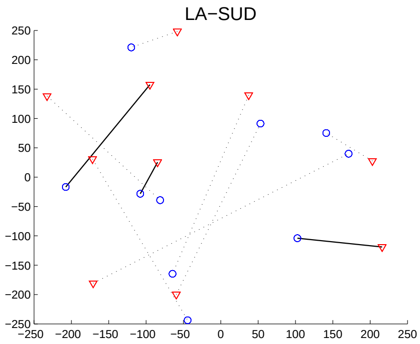


(d) N dataset; dense topology

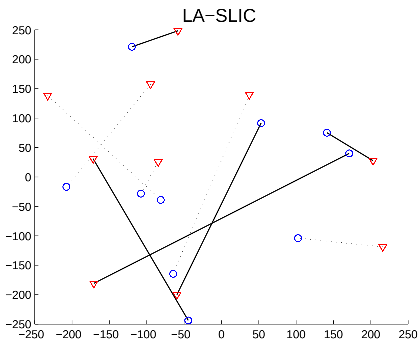
Fig. 2. Distribution of SNR for different datasets and densities.

dataset N. In this dataset, the length of the links is constrained to be from 3m up to 200m, with the rationale to produce instances resembling a multihop network. The networks considered have cardinality K ranging from 5 up to 30 links. Fig. 1 illustrates instances of a 20-link network; Figs. 1a and 1c correspond to the sparse and dense topology, respectively, of dataset I, whereas Figs. 1b and 1d correspond to the sparse and dense topology, respectively, of dataset N.

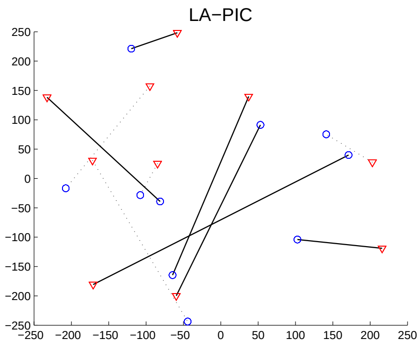
The input parameters are chosen to be common for all links; specifically, the transmit power p_k, $\forall k \in \mathcal{K}$, is set to 30dBm, the noise power η to -100dBm, and the channel gains G_{mk} follow the geometric, distance-based, path loss model with an exponent of 4. The major difference between the datasets is the distribution of the link lengths, which effectively determines the SNR distribution of the links. The input parameters yield minimum SNR approximately equal to 4dB, 16dB, and 32dB for dataset sparse I, dense I, and N, respectively. The histograms in Fig. 2 illustrate the SNR distribution of each dataset; as in Fig. 1, left and



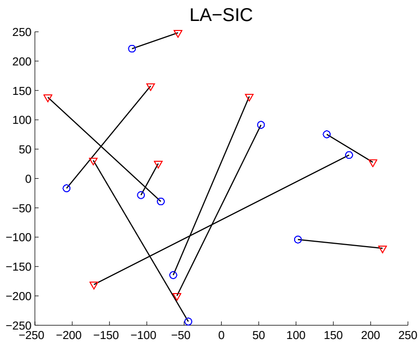
(a) LA-SUD



(b) LA-SLIC



(c) LA-PIC

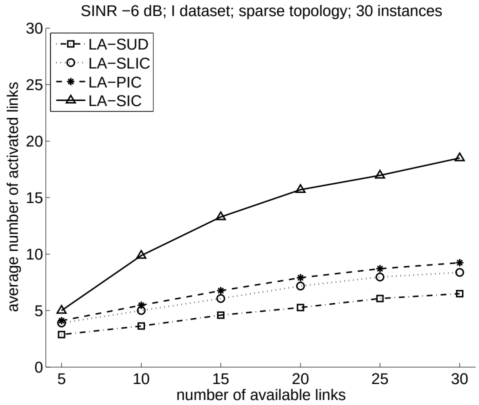


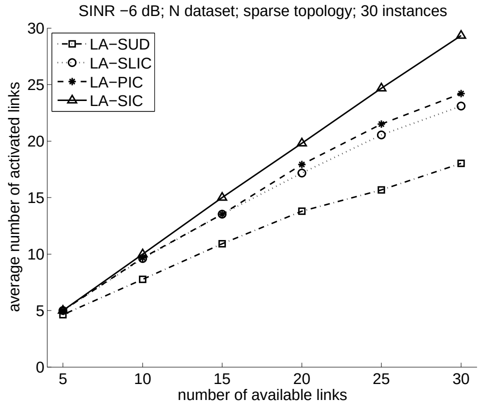
(d) LA-SIC

Fig. 3. Exemplary activation sets for different IC schemes; I dataset; dense topology; 10 links; SINR -9dB.

right sub-figures are for dataset I and N, respectively, whereas upper and lower sub-figures are for sparse and dense topologies, respectively. For dataset I, the links in the sparse topology have on average lower SNR than in the dense topology; the mass of the SNR distribution is roughly for 10–40dB in the sparse and for 20–50dB in the dense topology. This is because in the sparse topology the test area is enlarged, allowing generation of longer links which have lower SNR values. On the contrary, the SNR distribution of dataset N is invariant to the network density; this is by construction, since the distribution of the link lengths is not affected by the size of the test area.

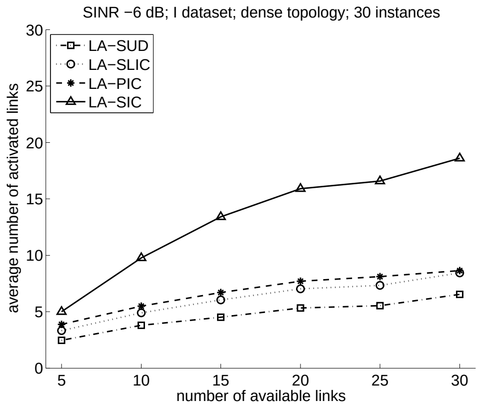
For each dataset and network cardinality, 30 instances are generated and the performance of LA with IC is assessed by two simulation studies. In the first study, all links are assumed to require for activation a common SINR threshold $\gamma_k = \gamma$, $\forall k \in \mathcal{K}$, taking values from -9dB up to 6dB, and have equal activation weights, e.g., $w_k = 1$, $\forall k \in \mathcal{K}$. The goal is to evaluate the performance gain due to single-link, parallel, and successive IC schemes on the LA problem over the baseline approach without IC. For this purpose, we implemented

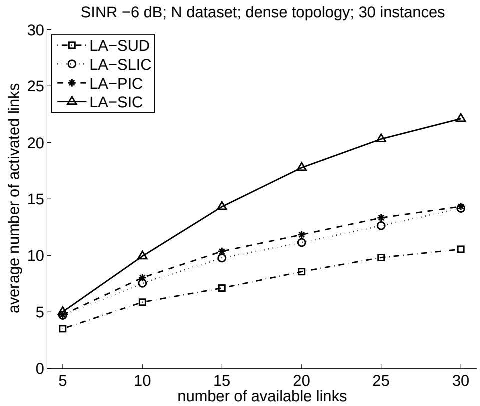




(a) I dataset; sparse topology

(b) N dataset; sparse topology





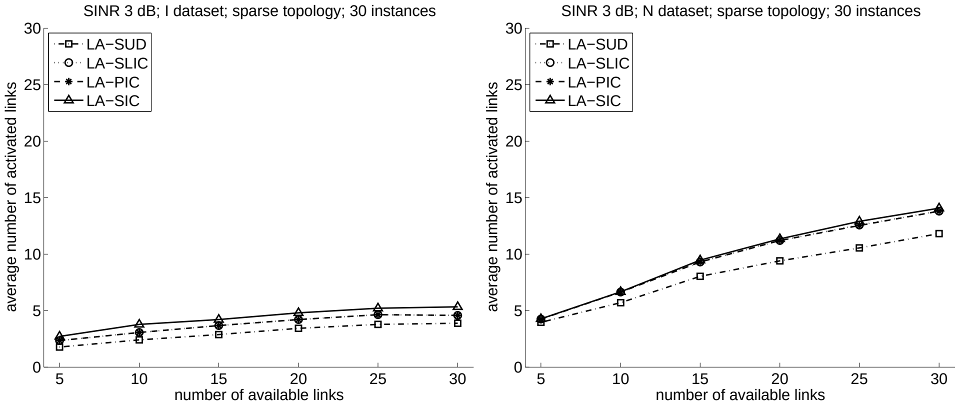
(c) I dataset; dense topology

(d) N dataset; dense topology

Fig. 4. Average number of activated links versus network size for SINR threshold -6dB.

the formulations (5), (11)–(12), (11), and (13), for LA-SUD, LA-SLIC, LA-PIC, and LA-SIC, respectively. Fig. 3 illustrates exemplary activation sets for an instance of a 10-link network, drawn from dataset dense I, when the SINR threshold is -9dB. It is evidenced that performance increases with problem sophistication: Figs. (3a), (3b), (3c), and (3d), show that LA-SUD, LA-SLIC, LA-PIC, and LA-SIC activate 3, 5, 6, and 10 links, respectively.

The optimal solutions are found by an off-the-shelf solver, implementing standard techniques such as branch-and-bound and cutting planes [5]. The simulations were performed on a server with a quad-core AMD Opteron processor at 2.6 GHz and 7 GB of RAM. The ILP formulations were implemented in AMPL 10.1 using the Gurobi Optimizer ver. 3.0. Regarding the computational complexity of the proposed ILP formulations for IC, an empirical measure is the running time of the solution process. We have observed that it is not an obstacle for practical instance sizes.

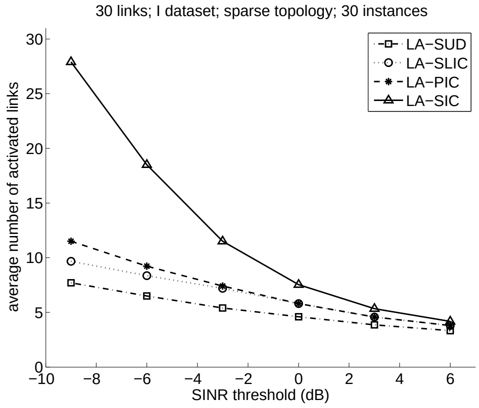


(a) I dataset; sparse topology (b) N dataset; sparse topology

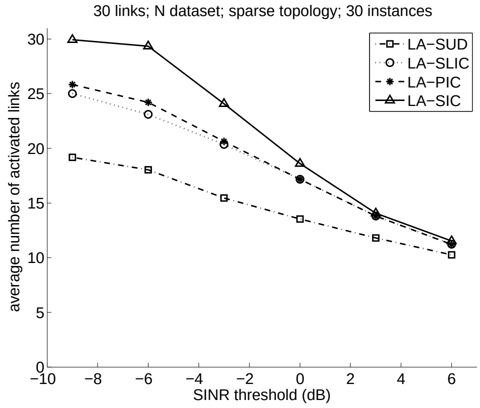
Fig. 5. Average number of activated links versus network size for SINR threshold 3dB.

In the following a selection of the simulation results is presented. Fig. 4 shows the average, over 30 instances, number of activated links versus the total number of links in the network, achieved by all versions of the LA problem when the SINR threshold is -6dB. The results in the four sub-figures correspond to the datasets exemplified in Fig. 1. The major observation is that all LA schemes with IC clearly outperform LA-SUD and in particular LA-SIC yields impressive performance. Comparing Figs. 4a and 4c, it is concurred that the results for dataset I are density invariant. As the number of links in the network increases, the performance of LA-SUD improves, due to the diversity, almost linearly but with very small slope. LA-SIC though improves significantly, activating two to three times more links than the baseline. When the network has up to about 15 links, nearly all of them are activated with LA-SIC. On the other hand, LA-PIC has a consistent absolute gain over LA-SUD, activating one to two links more. Furthermore, LA-SLIC has almost as good performance with LA-PIC, i.e., it captures most of the gain due to single-stage IC. Fig. 4d shows that the LA schemes have similar performance in dataset dense N as in dataset I. Fig. 4b shows that LA is easier for dataset sparse N, even without IC. The curves of all schemes linearly increase with network cardinality, but with IC the slopes are higher, so that the absolute gains, differences from the baseline, broaden. Maximum gains are for 30 links, where LA-SUD, LA-SLIC, LA-PIC, and LA-SIC activate about 18, 22, 23, and 30 links, respectively. For the tested network cardinalities, LA-SIC achieves the ultimate performance activating all links.

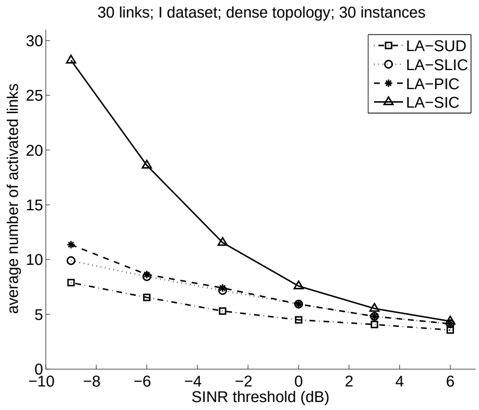
As seen in Fig. 4, the performance gains due to IC are very significant when the SINR threshold for activation is low. However, for high SINR thresholds, the gains are less promi-



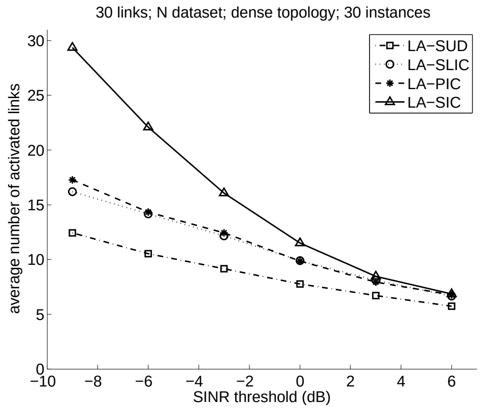
(a) I dataset; sparse topology



(b) N dataset; sparse topology



(c) I dataset; dense topology

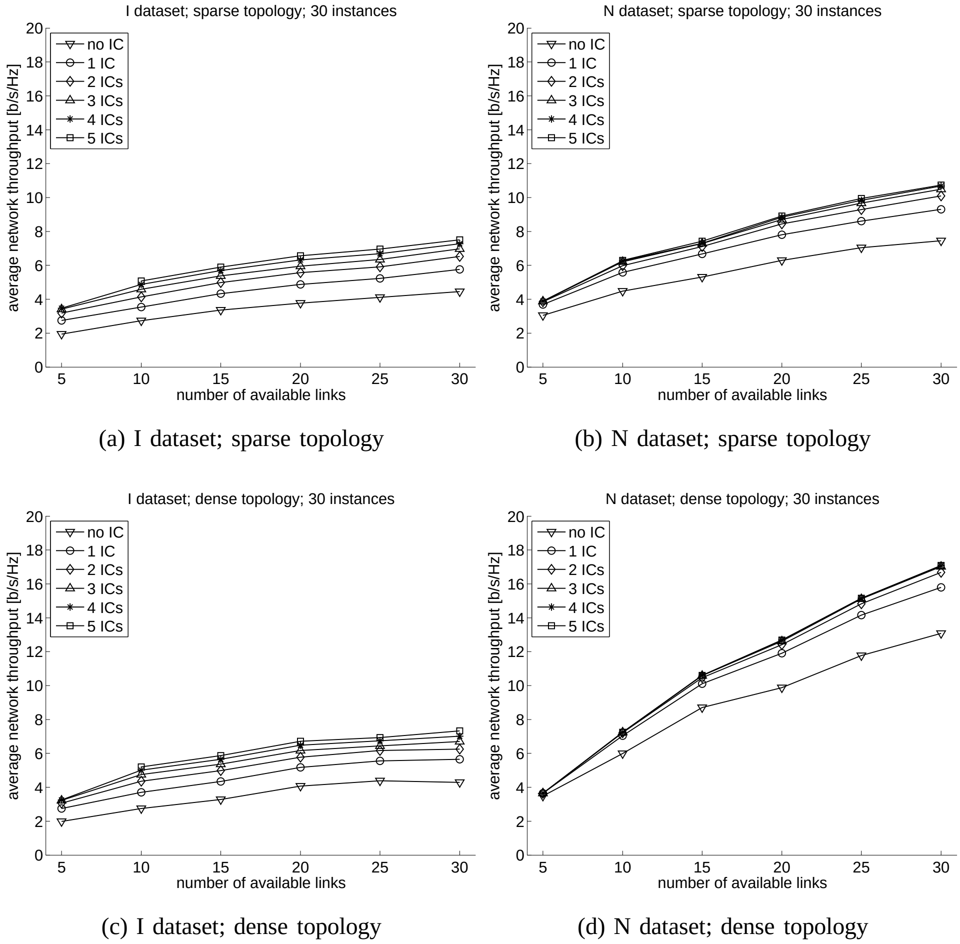


(d) N dataset; dense topology

Fig. 6. Average number of activated links versus SINR threshold for network of 30 links.

nent. For example, Fig. 5 shows the performance of the LA schemes when γ is set to 3dB. Figs. 5a and 5b are for the sparse datasets I and N, respectively; for the dense topologies the results are similar to Fig. 5a. It is evidenced that IC schemes activate one to two links more than the baseline and that most of this gain can be achieved with single-stage IC.

The fact that the IC gains diminish with increasing the SINR threshold is clearly illustrated in Fig. 6, which compares, for networks of 30 links, the average performance of all LA schemes for various SINR thresholds. The relative gain of SIC is more prominent in the case of dataset I, which is more challenging for the baseline problem. For dataset I, when the SINR threshold is low, around -9dB, SIC activates nearly all links, whereas SUD activates less than a third of them. For sparse and dense dataset N, SIC activates effectively all links when the SINR threshold is lower than -6dB and -9dB, respectively, whereas SUD activates less than two thirds and less than half of them, respectively. For mid-range SINR thresholds,



(a) I dataset; sparse topology (b) N dataset; sparse topology

(c) I dataset; dense topology (d) N dataset; dense topology

Fig. 7. Average network throughput versus network cardinality for various IC schemes and SINR thresholds randomly chosen from $\{-6, -3, 3\}$dB.

up to about 3dB, SIC has an exponentially decreasing performance, but nevertheless still significantly outperforms SUD. On the other hand, for SINR thresholds up to about 0dB, PIC yields a relatively constant performance improvement of roughly two to five links, depending on the dataset. PIC is effectively equivalent to its simpler counterpart SLIC, for SINR higher than -6dB. The performance of all IC schemes converges for SINR thresholds higher than 3dB. The interpretation is that if IC is possible, it is more likely that it will be restricted to a single link. For very high SINR thresholds, it becomes rarely possible to perform IC.

In the second simulation setup, the performance of the general LA-SIC problem, under individual SINR thresholds, is evaluated. The SINR threshold γ_k for each link is taking, with equal probability, one of the values in the set $\{-6, -3, 3\}$dB and the activation weights w_k are set equal to the data rates, in bits per second per Hertz, corresponding to the respective SINR thresholds. The formulation (14) is implemented varying the maximum number of

cancellation stages $T_k = T$, $\forall k \in \mathcal{K}$, from 0, corresponding to the baseline case without IC, up to 5. Fig. 7 shows the average, over 30 instances, throughput of all activated links versus the network cardinality, for all the datasets. For dataset I, the network throughput is almost doubled with IC; roughly half of this increase is achieved by the first cancellation stage and most of the rest by the next two to three stages. For dataset N, it is seen that the first cancellation stage yields a significant gain of about 2 b/s/Hz and that it only pays off to have more than two cancellation stages for large and sparse networks.

VIII. Conclusions

In this paper, we have addressed the problem of optimal concurrent link activation in wireless systems with interference cancellation. We have proved the NP-hardness of this problem and developed integer linear programming formulations that can be used to approach the exact optimum for parallel and successive interference cancellation. Using these formulations, we have performed numerical experiments to quantitatively evaluate the gain due to interference cancellation. The simulation results indicate that for low to medium SINR thresholds, interference cancellation delivers a significant performance improvement. In particular, the optimal SIC scheme can double or even triple the number of activated links. Moreover, node density may also affects performance gains, as evidenced in one of the datasets. Given these gains and the proven computational complexity of the problem, the development of approximation algorithms or distributed solutions incorporating IC are of high relevance.

Concluding, the novel problem setting of optimal link activation with interference cancellation we have introduced here provides new insights for system and protocol design in the wireless networking domain, as in this new context, strong interference is helpful rather than harmful. Thus, the topic calls for additional research on resource allocation schemes in scheduling and routing that can take the advantage of the interference cancellation capability. Indeed, the LA setup studied herein assumes fixed transmit power for active links. This can lead to increased interference levels, since the SINRs can be oversatisfied. Incorporating power control to the LA problem with IC will bring another design dimension which can yield additional gains. Furthermore, it may enable IC for high SINR thresholds IC.

REFERENCES

[1] R. Ahlswede, “The capacity region of a channel with two senders and two receivers,” *Ann. Probab.*, vol. 2, pp. 805–814, 1974.

[2] M. Andrews and M. Dinitz, “Maximizing capacity in arbitrary wireless networks in the SINR model: complexity and game theory,” *Proc. IEEE INFOCOM*, 2009.

[3] V. Angelakis, L. Chen, and D. Yuan, “Optimal and collaborative rate selection for interference cancellation in wireless networks,” *IEEE Commun. Lett.*, vol. 15, no. 8, pp. 819–821, 2011.

[4] V. S. Annapureddy and V. V. Veeravalli, “Gaussian interference networks: sum capacity in the low interference regime and new outer bounds on the capacity region,” *IEEE Trans. Inf. Theory*, vol. 55, no. 6, pp. 3032–3050, 2009.

[5] D. Bertsimas and J. N. Tsitsiklis, *Introduction to Linear Optimization.* (Athena Scientific), 1997.

[6] P. Björklund, P. Värbrand, and D. Yuan, “Resource optimization of spatial TDMA in ad hoc networks radio networks: a column generation approach,” *Proc. IEEE INFOCOM ’03*, pp. 818–824, 2003.

[7] P. Björklund, P. Värbrand, and D. Yuan, “A column generation method for spatial TDMA scheduling in ad hoc networks,” *Ad Hoc Netw.*, vol. 2, pp. 405–418, 2004.

[8] S.A. Borbash and A. Ephremides, “The feasibility of matchings in a wireless network,” IEEE Trans. Inf. Theory, vol. 52, no. 6, pp. 2749–2755, 2006.

[9] G. Brar, D. M. Blough, and P. Santi, “Computationally efficient scheduling with the physical interference model for throughput improvement in wireless mesh networks,” *Proc. ACM MobiCom*, 2006.

[10] A. Capone and G. Carello, “Scheduling optimization in wireless mesh networks with power control and rate adaptation,” *Proc. IEEE SECON*, 2006.

[11] A. Capone, G. Carello, I. Filippini, S. Gualandi, and F. Malucelli, “Routing, scheduling and channel assignment in wireless mesh networks: optimization models and algorithms,”, *Ad Hoc Netw.*, vol. 8, pp. 545-563, 2010.

[12] A. Capone, L. Chen, S. Gualandi, and D. Yuan, “A new computational approach for maximum link activation in wireless networks under the SINR model,” *IEEE Trans. Wireless Commun.*, vol. 10, no. 5, pp. 1368–1372, 2011.

[13] A. B. Carleial, “Interference channels,” *IEEE Trans. Inf. Theory*, vol. 24, pp. 60–70, 1978.

[14] J. El-Najjar, C. Assi, and B. Jaumard, “Joint routing and scheduling in WiMAX-based mesh networks,” *IEEE Trans. Wireless Commun.*,, vol.9, no.7 pp. 2371–2381, 2010.

[15] L. Fu, S.C. Liew, and J. Huang, “Fast algorithms for joint power control and scheduling in wireless networks,” *IEEE Trans. Wireless Commun.*, vol.9, no.3, pp.1186-1197, 2010.

[16] R. Ghaffar and R. Knopp, “Spatial iterference cancellation algorithm,” *Proc. IEEE WCNC*, 2009.

[17] A. Gjendemsj, *et al.* “Binary power control for sum rate maximization over multiple interfering links,” *IEEE Trans. Wireless Commun.*, vol.7, no.8, pp.3164-3173, 2008.

[18] O. Goussevskaia, Y. A. Pswald, and R. Wattenhofer, “Complexity in geometric SINR,” *Proc. ACM MobiHoc*, 2007.

[19] P. Gupta and P. R. Kumar, “The capacity of wireless networks,” *IEEE Trans. Inf. Theory*, vol. 46, pp. 388–404, 2000.

[20] M. Haenggi, “On distances in uniformly random networks,” *IEEE Trans. Inf. Theory*, vol. 51, no. 10 pp. 3584–3586, 2005.

[21] B. Hajek and G. Sasaki, “Link scheduling in polynomial time,” *IEEE Trans. Inf. Theory*, vol.34, no.5, 1988.

[22] T. Han and K. Kobayashi, “A new achievable rate region for the interference channel,” *IEEE Trans. Inf. Theory*, vol. 27, pp. 49–60, 1981.

[23] K. Jain, *et al.*, ”Impact of interference on multi-hop wireless network performance,” *Proc. ACM MobiCom*, 2003.

[24] E. Karipidis, D. Yuan, and E. G. Larsson, “Mixed-integer linear programming framework for max-min power control with single-stage interference cancellation,” *Proc. IEEE ICASSP*, 2011.

[25] S. Katti, S. Gollakota, and D. Katabi, “Embracing wireless interference: analog network coding”, *Proc. ACM SIGCOMM*, 2007.

[26] Y. Li and A. Ephremides, “A joint scheduling, power control, and routing algorithm for ad hoc wireless networks,” *Ad Hoc Netw.*, vol. 5, pp. 959–973, 2007.

[27] S. Lv, *et al.*, “Scheduling in wireless ad hoc networks with successive interference cancellation,” *Proc. IEEE INFOCOM*, 2011.

[28] R. Nelson and L. Kleinrock, “Spatial TDMA: a collision-free multihop channel access protocol,” *IEEE Trans. Commun.*, vol. 33, pp. 934–944, 1985.

[29] A. Pantelidou, and A. Ephremides, “The scheduling problem in wireless networks,” *Journal of Communications and Networks*, vol. 11, no. 5, 2009.

[30] X. Shang, G. Kramer, and B. Chen, “A new outer bound and the noisy-interference sum-rate capacity for Gaussian interference channels,” *IEEE Trans. Inf. Theory*, vol. 55, no. 2, pp. 689–699, 2009.

[31] S. Srinivasa and M. Haenggi, “Distance distributions in finite uniformly random networks: theory and applications,” *IEEE Trans. Vehicular Technol.*, vol. 59, no. 2, pp. 940–949, 2010.

[32] L. Tassiulas, and A. Ephremides, “Stability properties of constrained queueing systems and scheduling for maximum throughput in multihop radio networks,” *IEEE Trans. on Automat. Contr.*, vol. 37, no. 12, pp. 1936-1949, 1992.

[33] S. Verdu, *Multiuser decoding*, Cambridge, U.K.: Cambridge Univ. Press, 1998.

[34] C. Weeraddana, M. Codreanu, and M. Latva-aho, “On the Advantages of Using Multiuser Receivers in Wireless Ad-Hoc Networks,” *Proc. IEEE VTC 2009-Fall*, 2009.

[35] L. A. Wolsey, *Integer Programming*, John Wiley & Sons, New York, 1998.

[36] X. Xu and S. Tang, “A constant approximation algorithm for link scheduling in arbitrary networks under physical interference model,” *Proc. ACM FOWANC*, 2009.